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Experimental investigation of Wall Friction in Vertical Annular Channels under Natural Circulation Flow

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1. Introduction

Natural circulation flow is widely adopted in recent reactor designs as a passive safety mechanism for heat removal [1-5]. Its magnitude is determined by the balance between buoyancy and pressure losses within the loop. Depending on the relative strength of buoyancy and inertia, the convection regime is classified as forced, mixed, or natural convection. This convection regime governs the local thermal-hydraulic behavior in the loop.

Natural circulation flow under pressurized conditions plays a critical role in progression of accidents such as SBO, LOFA. Meanwhile, vertical annular channels have been proposed as candidate core geometries for advanced reactors [6-9]. However, existing experimental data on wall friction in such channels are limited, particularly under high-pressure and high-temperature water conditions. Therefore, this study conducts experiments under these conditions for natural circulation flow in vertical annular channels with various gaps. Based on the experimental data, a wall friction correlation is developed for mixed convection regime.

2. Experimental Setup

A closed-loop test facility was constructed for natural circulation experiments under water flow conditions up to 30 bar and 235 °C. The details of the test section and measurement methods are described in the following sections.

2.1 Test Section

As depicted in Fig. 1, the test section was a vertical concentric annular channel with gap sizes of 2.9, 5, and 7 mm. An electrically heated rod with a 9.5 mm diameter and 804 mm heated length was installed at the center. To maintain alignment, two supporting grids were placed at 0.2 m and 0.84 m from the bottom. K-type thermocouples with a sheath diameter of 0.5 mm measured local fluid temperatures along the gap centerline. The pressure drop across the upper part of the test section (0.55–0.81 m) was measured using a differential pressure transmitter. A flow conditioner was placed at the test section inlet to minimize flow development effects. An optical fiber probe at the top of the heated section detected vapor formation.

A supporting grid was installed upstream of the pressure measurement section, and four thermocouples were placed within the section to measure fluid temperature. These components could introduce form losses. However, an additional test confirmed that the form losses were smaller than the uncertainty of the pressure transmitter and thus negligible in the wall friction analysis.

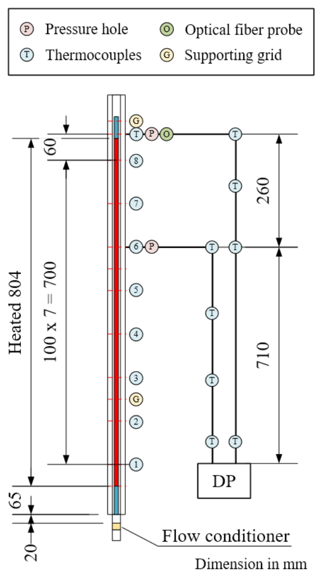

Fig. 1. Schematic of the vertical annular test section.

2.2 Measurement Methods

The wall friction factor was calculated using the measured pressure drop and the cross-sectional average fluid temperature. The average temperature was obtained from an energy balance equation accounting for heat loss in the test section.

Under low-flow conditions, the measured pressure difference ranged from 30 to 120 Pa. Heat conduction from the test section heated the fluid in the impulse lines, thereby affecting the hydrostatic pressure of the lines. To consider this effect, four thermocouples were installed along the vertical section of each impulse line. The measured temperature profiles were used to estimate the liquid density for hydrostatic pressure compensation. Finally, the wall friction factor was calculated as follows:

$$f = 2\frac{D_h}{L}\frac{DP_{read}+\{g(\rho_{H,avg}h_H-\rho_{L,avg}h_L-\rho_{TS,avg}L)\}}{\rho_{TS,avg}v_{avg}^2} \quad (1)$$

All instruments were calibrated to minimize measurement uncertainty. The estimated uncertainties were as follows: ±0.61 °C for thermocouples, ±1.5 Pa for the pressure transmitter, ±1.3 g/s (11.5 kg/m^{2}s for 2.9 mm gap) for the coriolis flowmeter, and ±89 W (3709 W/m^2) for the power meter.

3. Experimental Results

Natural circulation experiments were conducted under the conditions listed in Table 1. Fig. 2 presents a comparison of measured wall friction factors with existing forced convection friction models.

For the 2.9 mm gap, the friction factor decreased with increasing Reynolds number (*Re*) and showed a transition in the range of 1,000 < *Re* < 3,000. In this range, the fluid temperature at the channel center oscillated with an amplitude of 10°C in the upper part of the test section, indicating the onset of turbulence.

In the 5 mm case, the friction factor gradually decreased and converged to a constant value at *Re* > 3,000. The measured values exceeded the predictions of existing forced convection correlations [10, 11], indicating an enhanced influence of buoyancy.

The friction factor for the 7 mm gap increased with inlet temperature. The deviation from forced convection models became most significant under these conditions.

In summary, larger gaps led to higher wall friction due to buoyancy-induced secondary flows and viscous dissipation. The results highlight the limitations of the existing friction models based only on *Re* and suggest the need for additional thermal-hydraulic parameters to improve prediction accuracy.

Table I: Experimental Conditions

Pressure (bar)	Inlet fluid temperature (°C)	Mass flux (kg/m^{2}s)	Heat flux (kW/m^2)	*Re* (-)
30	40-160	23-165	37-310	670-4,980

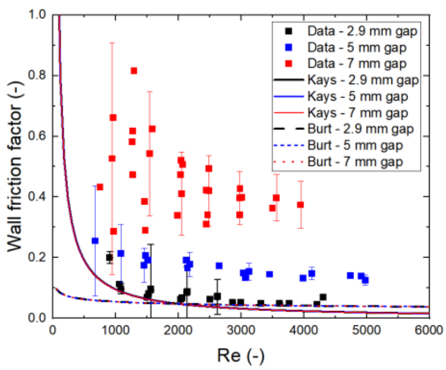

Fig. 2. Comparison between experimental data and forced convection wall friction models.

4. Development of a New Wall Friction Model

To model the nonlinear relationship between the wall friction factor and thermal-hydraulic variables, a hybrid machine learning framework [12] combining a Deep Belief Network (DBN) and a Residual Network (ResNet) was employed. In this framework, the DBN performs unsupervised feature extraction, while ResNet stabilizes supervised learning through residual connections.

A total of 14 dimensionless parameters including $Ri\,(Gr/Re^2)$, $Pr\,(c_p\mu/k)$, $Gr\,(g\beta(T_w-T_b)D_h^3/\nu^2)$, $Re(\rho v D_h/\mu)$, $N(g\beta D_h/c_p)$, $\Delta\rho(\rho_w/\rho_f)$, $\Delta\mu(\mu_w/\mu_f)$, and $La(\sigma\rho D/\mu^2)$ were used as input parameters for machine learning. Since surface roughness of all test sections was less than 5 μm, its effect was neglected based on the existing model [13]. The output variable was the normalized friction factor, where the references for the normalization were the Kays model [10] for *Re* < 2,000 and the Burt correlation [11] for *Re* > 2,000. Based on the data preparation, the model was trained with 185 experimental data points, achieving $R^2 = 0.92$ and MAPE = 14.3%.

To interpret the trained model, a partial dependence plot (PDP) analysis was performed. The analysis revealed that *Ri, La, N,* and *Pr* were the most influential variables. Although *La* consists of viscosity, density, and length scale correlated with buoyancy and viscous effect, *La* was excluded from the analysis due to limited physical relevance of surface tension in single-phase wall friction. *N* represents the ratio of the kinetic energy generated by buoyancy to the thermal capacity of the fluid, indicating the relative importance of viscous dissipation [14]. The trained model showed consistent trends with previous studies [15-18], indicating that the friction factor increased with *Ri* and *N*, and decreased with *Pr*. Based on this analysis, a new correlation was developed, as presented in Eq. (2).

$$f/f_{FC} = 24N^{-0.026}Pr^{-1.9}(1-0.96e^{-0.16Ri}) \quad (2)$$

The correlation was derived from the experimental data within the range of $7.9\times10^{-9} < N < 3.1\times10^{-8}, 1.15 < Pr < 2.72, 0.13 < Ri < 4.86$. The new correlation achieved $R^2 = 0.88$ and MAPE = 22.5%, as shown in Fig. 3.

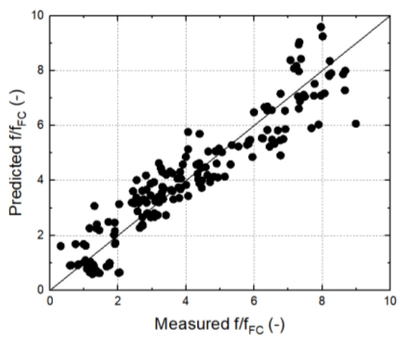

Fig. 3. Comparison between experimental data and proposed wall friction model.

5. Conclusions

This study experimentally investigated wall friction in vertical annular channels under single-phase natural circulation water flow at high pressure and temperature. The results confirmed that the existing forced convection correlations are limited for predicting wall friction in mixed convection regimes. To address this limitation, a new correlation was developed, and its functional form was determined based on the interpretation of the machine learning results. The proposed correlation can be useful for predicting wall friction factors in the mixed convection regime of natural circulation flow.

NOMENCLATURES

c_p	Specific heat [J/kgK]
DP_{read}	Reading value of DP transmitter [Pa]
D_h	Hydraulic diameter [m]
f	Friction factor [-]
g	Gravitational acceleration [m/s^2]
Gr	Grashof number $(g\beta(T_w - T_b)D_h^3/\upsilon^2)$ [-]
h	Height [m]
k	Thermal conductivity [W/mK]
L	Measuring length [m]
La	Laplace number $(\sigma\rho D/\mu^2)$
N	Viscous dissipation parameter $(g\beta D_h/c_p)$ [-]
Pr	Prandtl number $(c_p\mu/k)$ [-]
Re	Reynolds number $(\rho v D_h/\mu)$ [-]
Ri	Richardson number (Gr/Re^2) [-]
T	Temperature [K]
v	Velocity [m/s]

Greeks

β	Thermal expansion coefficient [1/K]
μ	Viscosity [Pa·s]
υ	Kinematic viscosity [m^2/s]
ρ	Density [kg/m^3]
σ	Surface tension [N/m]
Δ	Wall-to-fluid ratio

Subscripts

avg	Average
f	Fluid
FC	Forced convection
H	Impulse line for higher pressure
L	Impulse line for lower pressure
TS	Test section
w	Wall

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